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Modelling the Economic Impacts of Climate Change on Global and European Agriculture. Review of Economic Structural Approaches

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Abstract

The economic effects of climate change on agriculture have been widely assessed in the last two decades. Many of these assessments are based on the integration of biophysical and agro-economic models, allowing to understand the physical and socio-economic responses of the agricultural sector to future climate change scenarios. The evolution of the bio-economic approach has gone through different stages. This review analyses its evolution: firstly, framing the bio-economic approach into the context of the assessments of climate change impacts, and secondly, by reviewing empirical studies at the global and European level. Based on this review, common findings emerge in both global and regional assessments. Among them, the authors show that overall results tend to hide significant disparities on smaller spatial scales. Furthermore, due to the effects of crop prices over yield changes, several authors highlight the need to consider endogenous price models to assess production impacts of climate change. Further, major developments are discussed: the progress made since the last two decades and the recent methods used to provide insights into modeling uncertainties. However, there are still challenges to be met. On this matter, the authors take these unresolved challenges as guidelines for future research.

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Keywords Climate change, economic modelling, agricultural markets, food security, food prices

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1 Introduction

Assessing the economic effects of climate change on agriculture implies identifying and analysing biophysical and socio-economic aspects (Blanco et al., 2014a). To address this challenge, several climate change impact assessments, have based their methodology on structural approaches that integrate biophysical and economic models. Amongst the different ways of modelling integration, the projected yield impacts as inputs to general or partial equilibrium models of commodity trade have been widely used for economic assessments of climate change impacts. This approach, has evolved over the years thanks to several improvements in the various aspects underlying this methodology, including improved computer capacities, greater data availability, and the wider scope of biophysical and economic models.

This review addresses three objectives. 1) To specify the structural approach when assessing the economic impacts of climate change on agriculture, distinguish it from other approaches, and define the different methods that rely on it. 2) To review the evolution and use of structural approaches that integrates biophysical and economic models for studying the impacts of climate change on agriculture. 3) To identify common findings through the evolution of this approach and the main shortcomings that should be overcome by future research.

This article builds on the Intergovernmental Panel on Climate Change (IPCC) assessment reports, with special attention given to the chapters that focus on reviewing the economic impacts of climate change on global and European Union (EU) agriculture. Several other studies have been included in our analysis, including studies published in peer-reviewed journals and some selected scientific reports (all of which are available online).

This review is organised as follows. Section 2 fulfils two objectives. First, it provides an overview of the main approaches used for evaluating the economic effects of climate change on agriculture and establishes the structural approaches as the focus of our review. Second, it describes the different methods and their variants within this specific approach. Within this context, Section 3 analyses both global and European economic assessments regarding the impacts of climate change on agriculture, highlighting their main differences and similarities. Section 4 reviews recent assessments based on the new Fifth Assessment Report of the IPCC (AR5) Representative Concentration Pathways (RCPs) and the Shared

Socioeconomic Pathways (SSPs). Finally, Section 5 summarises the main findings from the literature, highlights the main lessons learned and proposes future research directions for global and European assessments.

A summary of reviewed global and European papers, their modelling approaches, data, regional scope and time horizon is presented in annex tables 1 and 2 of the appendices. All of these studies are framed within the development/updating process of IPCC assessments and special reports.

2 Economic assessment methods, overview and focus of the study

A vast amount of literature is available regarding assessing the effects of climate change on agriculture. Broad categorisation divides these assessments into agriculturally oriented studies that focus on the responses of crops to climatic variations and economically oriented studies that consider the economic responses to changes in crop yield (Bosello and Zhang, 2005; Iglesias et al., 2011). Within agriculturally oriented studies, three main approaches have been distinguished, biophysical process-based models (Jones et al., 2011; Challinor et al., 2004; van Ittersum and Donatelli, 2003), agro-ecosystem models (Fischer et al., 2002), and the statistical analysis of historical data (Lobell and Burke, 2010b). Recent reviews (White et al., 2011; Ewert et al., 2014) offer a comprehensive examination of this field, especially the field of crop modelling, to assess the impacts of climate change. Within the economically oriented category, the common taxonomy used for these approaches was proposed by Schimmelpfennig et al. (1996) and Adams et al. (1998) which divided them into "spatial-analogue approaches" and "structural approaches". The specific aspects and features for each approach are discussed below.

2.1 Spatial-analogue approach

This approach is mainly based on econometric techniques that analyse changes in spatial production patterns. Information collected from farmers operating across a range of conditions can be used to infer and predict how future changes may affect profits. Thus, this approach can be used to estimate the impacts of climate change based on observed differences (Adams, 1999). Here, possible adaptations are embedded in the information collected regarding the farmer's behaviour, which is the main difference between this approach and the structural approach. We found two methods amongst the spatial-analogue, the Ricardian approach that estimates adaptations using cross-sectional statistics and econometric techniques (e.g., Mendelsohn et al., 1994, 1996), and the duality-based model that uses geographic information systems combined with an economic model (e.g., Darwin et al., 1995; Darwin, 1999)[1]. Regardless of the method used, both methods assume that variations in land values reflect the welfare implication of the impacts of climate change.

The spatial-analogue approach is a powerful tool used for capturing the effects in the data used for the analysis. The main advantage of this approach over the structural approach is that the analyst does not have the responsibility for estimate possible adaptations. However, limitations are associated with the nature of these assumed responses. For example, the spatial analogue abstracts from the costs of changes in structural characteristics, which may be necessary to mimic practices in warmer climates (e.g., irrigation systems). Additionally, the assumption that agricultural prices do not respond to changes in land prices ignores the future impacts of price changes on supply and demand (Bosello and Zhang, 2005). Furthermore, this approach can only capture the effects observed in the data, questioning its plausibility for long-term projections (Nelson et al., 2014).

Besides the seminal works mentioned above, several studies have used the spatial-analogue approach to assess the economic effects of climate change on agriculture. This approach has been applied in the USA (Mendelsohn and Dinar, 2003), Africa (Kurukulasuriya et al., 2006), Europe (van Passel et al., 2014), South America (Seo and Mendelsohn, 2008), and several countries (Reinsborough, 2003; Wang et al., 2009), mainly by using the Ricardian method.

2.2 Structural approach

Unlike the spatial-analogue approach, this approach simulates crop and farmer responses based on the economic structural relationships suggested by theory, which are specified rather than estimated (Adams, 1999). Additionally, this approach

[1] Although Adams (1999) highlights that one of its component falls within the structural approach.

includes changes in land values within the economic models so that the responses of all economic agents are considered explicitly and include the direct effects of specific farm-level adaptations. In addition, this approach is inherently interdisciplinary when applied to climate change because it typically uses interlinked models from several disciplines (Freeman, 1993). The most common method within this approach consists of using biophysical models to predict the effects of crop yields on climate change scenarios that are used as input into the economic model to predict future socio-economic effects.

Amongst its strengths, this approach provides a more explicit representation of causal effects and adjustments of the agricultural sector to climate change (Shrestha et al., 2013). In addition, because the assessment capacity of economic models to changes in market conditions under climate change, this approach is more reliable for understanding the distributional consequences of climate change (Adams, 1999). Furthermore, one of the main weaknesses of this method compared with spatial-analogue approaches is related to the construction of these models and the data and time-intensive requirements for estimating their structural relationships and parameters.

Several economic assessments of the impacts of climate change on agriculture based on the structural approach have been published since the first IPCC report in 1990. After proposing the characterisation of different methods, we present an extended review of several studies performed from the mid-1990s at the global and European levels.

Categorising methods within the structural approach

Within the structural approach and for the studies reviewed here, we propose a taxonomy that differentiates between the six methodologies used to assess the economic effects of climate change (see Figure 1). These methods are organised based on their geographical scales and their treatment of the economic dimension. According to their geographical coverage, a common distinction is made between global and regional assessments, with different levels of disaggregation, such as country (Adams et al., 1995; Yates and Strzepek, 1998; Reilly et al., 2003; Dube et al., 2013) , state (Kaiser et al., 1993), or another sub-regional level. The economic dimension is mainly distinguished by the economic models used to quantify the economic responses, including 1) farm economic models; 2) partial equilibrium (PE) models; 3) computable general equilibrium (CGE) models; and 4) the Basic Linked System (BLS) trade model.

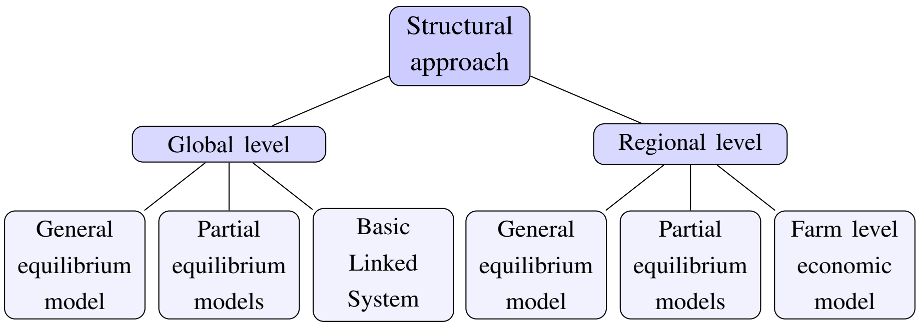

Figure 1: Proposed scheme for the different methodologies used within the structural approach.

Amongst these six categories, farm economic models are important tools for assessing the effects of climate change, mainly for production levels and farm income. Furthermore, farm economic models can focus on local adaptation options that would improve production levels and farm income in the face of climate change (see Kaiser et al., 1993). However, farm economic models ignore that economic estimates of damage from climate change must consider the global scale of these events. Additionally, when climate change would affect crop prices over time, these models are not suitable for capturing market feedback. Thus, global or multi-region models are needed that can determine changes in crop prices endogenously. These methodological and spatial differences with PE, CGE and BLS models make it difficult to compare farm economic model outputs with the results of the last three economic models. Thus, we focus on reviewing the studies that use projected yield impacts as input data for the CGE or PE models of commodity trade.

The main difference between the PE and CGE models is their scope of application. While PE models consider the agricultural system as a closed system without linkages with the rest of the economy, CGE models provide a complete representation of the national economies (Tongeren et al., 2001). Each modelling approach has particular features with strengths and weaknesses, and choosing the modelling approach depends on the objective of the assessment and on the problem at hand. Furthermore, we emphasise the distinction between CGE and the BLS trade model. Although the literature classifies the BLS trade model as a general equilibrium approach (Fischer, 1988), important features make it different from the other CGE models used for assessing the impacts of climate change on agriculture. For example, the high detail in the agricultural sector and its coarse aggregation (relative to the one-simplified non-agricultural sector) make the BLS model a type of hybrid model between PE and CGE models. While a detailed discussion about the features, strengths and weaknesses of each one of these models is beyond the scope of this review, in annex table 3 we summarise their main features, and differences.

Other classification schemes

Within the literature, several classification-schemes and wide concepts can be found that encompass the methodologies that we review in this article. First, the integrated assessment modelling (IAM) approach is a common concept used to categorise different modelling approaches to assess the impacts of climate change. The IAM approach, encompasses models made of sub-models from a variety of disciplines, producing results that allow scientists to study the interconnected physical, biological and social elements of global change problems by using common language and metrics. Regarding climate change, this is a wide concept in which sub-models may cover all or part of the subcomponents of a coupled social-natural system (Schneider and Lane, 2005).

Second, a common categorisation, within the literature, is based on the different ways that the models are linked. Amongst this categorisation the models are integrated by a so-called "soft-link" approach, where the outcomes from one model are used as inputs in the other, or a "hard-link" approach that integrates several models into a single modelling tool (Reilly and Willenbockel, 2010). Although there are many examples of model linking in agricultural economics, here, we focus specifically on PE or CGE models soft-linked to biophysical models.

Although the concepts mentioned above encompass the methodologies that we review here, they also encompass a variety of different methods that are beyond the scope of this article, including the following relevant applications.

- Several modelling frameworks (e.g., SEAMLESS, EuRuralis, SCENAR2020) that link different models to answer complex policy questions and deliver results that are consistent at global, national and regional levels (see Wolf et al. (2012), for the application of the SEAMLESS framework to assess the impacts of climate change on EU agriculture).

- Fully integrated modelling approaches used to simulate the following: 1) activities that result in GHG emissions; 2) the carbon cycle and other processes that determine the atmospheric GHG concentrations; 3) the responses of climate systems to changes in the atmospheric GHG concentrations; and 4) the environmental and economic system responses of key climate-related variables. Important examples include the IMAGE and AIM models applied in the Millennium Ecosystem Assessment (MA) scenario (see Reilly and Willenbockel (2010) for a detailed review).

In the next sections, we will focus on the development of studies within this framework that meet the following criteria: 1) structural approaches from the 1990s until present; 2) global assessments and studies at the EU-regional level; and 3) the methods that include market feedback through endogenous price models. We divide the studies into those that occurred following 1990 to the recent release of the new Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) and subdivided them into global and regional studies. Next, we concentrated on the assessments based on the new RCPs and SSPs scenarios at the global and EU levels.

3 Climate change impacts and global and European economic assessments

3.1 Assessment of the global economic impacts of climate change on agriculture

In the early 1990s, only a few global assessments integrated crop responses with economic models. Amongst them, the seminal works by Tobey et al. (1992) and Kane et al. (1992) introduced crop effects suggested by previous studies into the PE model SWOPSIM. Tobey et al. (1992) presented 15 different scenarios based on three simulation experiments and divided them into five concurrent yield reductions in the U.S., Canada and the European Community. Meanwhile, Kane et al. (1992) presented two different scenarios that reflected "moderate impacts" and "very adverse impacts". Both studies established the following common consensus regarding the role of trade and markets in economic impact assessments: "*global warming would not seriously disrupt the global agricultural market, mainly because the consequences would be diffused throughout the world through trade and inter-regional adjustments*". Additionally, these authors compared their results with the work of Adams et al. (1988), who only considered the impacts of climate change in the U.S. These authors observed smaller net welfare effects than Adams et al. (1988), which they hypothesised occurred because the impacts of climate change were offset by international price changes. Both of these studies were instrumental in establishing that climate change assessments could not be made based only on domestic yield effects.

A few years later, Rosenzweig and Parry (1994) were some of the first researchers to consider climate change with CO_2 fertilisation effects and examine the potential impacts of adaptation measures. In this study, the two following main components were considered: 1) estimations of potential crop yield changes and 2) estimations of world food trade responses. Climate change scenarios were created by changing the observed data based on doubled CO_2 simulations of three GCMs (GISS, GFDL and UKMO). Agricultural scientists in 18 countries estimated potential changes in crop yields by using compatible crop models and GCM scenarios at 112 sites. These estimations were used to assume national level production changes for all cereals in all countries based on the similarities between the crops

Table 1: Percentage range of changes in global cereal production and prices (Source: Rosenzweig and Parry, 1994)

Scenario	Production (% changes)	Price (% changes)
With CO_2 fertilization	∼ –1 to –8	∼ 24 to 150
With CO_2 and Ad. Level 1	∼ 0 to –5	∼ 10 to 100
With CO_2 and Ad. Level 2	∼ 1 to –2	∼ –5 to 35

∼ approximately equal to

and countries. Next, the results were aggregated into regional yield changes based on the regions defined in the BLS model. The main results of these models show that the world cereal production decreased between 11 and 20% in the climate change scenarios without direct CO_2 effects. The inclusion of CO_2 effects resulted in small global production decreases of 1 to 8%, which increased cereal prices by 24–145%. The scenarios that included different adaptation options indicated even fewer effects on production and prices when compared with the scenarios mentioned above (Table 1).Their results exhibit several findings that will be mentioned in future global assessments, including reduced impacts on high latitude countries compared with tropical countries; greater impacts on C4 crops due to their lower responses to increases in CO2 fertilisation; a large degree of spatial variations in crop yields across the globe; and lower impacts of climate change when adaptation measures are considered.

These three seminal works were the few structural studies cited in the Second Assessment Report (SAR) (Watson et al., 1996) that linked biophysical responses to climate change with economic models. Similar studies were also mentioned in the reports provided by Reilly and Hohmann (1993) and Reilly et al. (1994). Based on these studies, the report indicated that although the direction of change in global production resulting from climate change is still uncertain, changes in the aggregate level would be small to moderate. In addition, this report expands and updates the information contained in the First Assessment Report (FAR) and establishes a new generation of assessments that examines the impacts of climate change on agriculture. From this point forward, more accurate projections of climate change resulting from GHG forcing became available based on updated emission scenarios (Leggett et al., 1992).

Parry et al. (1999) used the same method as Rosenzweig and Parry (1994) to examine the potential impacts of climate change on crop yields, world food supply, and the risks of hunger. This study was different from previous studies, mainly because it used GCMs with better spatial resolutions and updated emission scenarios (IS92). These authors ran crop models for three future climate conditions (2020s, 2050s, and 2080s) that were predicted by the GCMs HadCM2 and HadCM3 based on an IS92 scenario. In contrast with other studies conducted during the mid-1990s (Darwin et al., 1995; Adams et al., 1998), this study predicts the actual price increases under modest climate change. Small detrimental effects on cereal production by 2080 were estimated by the HadCM2 climate change scenario and were predicted to result in a cereal price increase of 17%. By contrast, the greater negative impacts on the yields projected under HadCM3 resulted in a crop price increase of 45% by 2080, with severe effects regarding the risk of hunger, especially in developing countries. The authors indicate that these global results hide regional differences in the impacts of climate change. For instance, in the HadCEM2 scenarios, yield increases at high and high-mid latitudes resulted in production increases (e.g., in Europe and Canada). By contrast, yield decreases at lower latitudes (tropics) resulted in production decreases, an effect that could be exacerbated where the adaptive capacity is lower than the global average. Table 2 presents changes in cereal production that were estimated by Parry et al. (1999) at the global and regional levels to occur by 2080.

For a broader use than the IS92 scenarios in 2000, the IPCC released a new set of emission scenarios called SRES scenarios (Special Report on Emission Scenarios) (Nakicenovic and Swart, 2000), which were used in the Third and the Fourth Assessment Reports (TAR and AR4). From this point on, the number of studies that quantified the economic impacts of climate change on agriculture at the global level increased. In the first half of the 2000s, several assessments were published that presented biophysical and economic estimates that were made by considering socio-economic futures based on SRES scenarios.

Maintaining the same methodology as previous works (Rosenzweig and Parry, 1994; Parry et al., 1999), Parry et al. (2004) based their estimations on SRES scenarios.These authors used the HadCM3 GCM to run different emission scenarios

Table 2: Cereal production (% change) for different GCMs and across GCM scenarios by 2080 (Source: Parry et al., 1999)

Climate scenario (GCM-forcing)	Region	Cereal production change
HadCM2-IS92a	Global	∼ –2.1%
HadCM3-IS92a	Global	∼ –4.0%
Range across GCM scenarios	Range across countries	
	North America	∼ –10 to 3%
	Latin America	∼ –10 to 10%
	Western Europe	∼ 0 to 3%
	Eastern Europe	∼ –10 to 3%
	Asia	∼ –10 to 5%
	Africa	∼ –10 to 3%

∼ approximately equal to. Considering CO_2 fertilization and adaptation measures

(A1, A2, B1 and B2)[2] and generated seven different climate change scenarios.Each of these scenarios considered different paths for global crop yields; however, the paths did not diverge until the mid-century. Table 3 presents the impacts of climate change on global cereal production and prices under "Bs" (B1a -B2a-b) and "As" (A1FI - A2a-c) scenarios by 2080. When omitting CO_2, greater reductions in cereal production and larger increases in their prices are observed relative to the scenarios in which CO_2 fertilisation is included. When CO_2 effects are assumed, the differences in cereal production and prices between climate scenarios are less clear than in the scenarios without CO_2. This study confirms the negative impacts of climate change in developing regions and the fewer significant changes in developed regions as well as the moderated globally aggregated effects on world food production and prices when CO_2 fertilisation is assumed.

Fischer et al. (2002, 2005), assessed the global impacts of climate change on agro-ecosystems up to 2080. Their approach was mainly differentiated by using the agro-ecological zones (AEZ) model(see Fischer et al. (2002) for a detail

[2] used ensemble members A1Fl, A2a-c, B1a and B2a-b

Table 3: Global cereal production and prices (% change) for a different averages of As and Bs scenarios, with and without CO_2 fertilization by 2080 (from Parry et al., 2004)

Climate scenario (GCM-forcing)	Production (% change)	Price (% changes)
HadCM3-B1-B2		
Without CO_2	$\sim -5\%$	$\sim 98.3\%$
With CO_2	$\sim -1.7\%$	$\sim 14.6\%$
HadCM3-A1-A2		
Without CO_2	$\sim -10\%$	$\sim 320\%$
With CO_2	$\sim -1\%$	$\sim 15.2\%$

$\sim$ approximately equal to

description), and by maintaining previous modelling frameworks (SRES scenarios and the BLS model). Fischer et al. (2005), used 14 combinations of socio-economic and climate scenarios between the SRES scenarios and the 5 GCMs (see annex). Overall, these authors present moderate changes in crop prices under climate change, mainly due to the small net changes in the impacts of global climate change on crop production (global cereal production changes fall by 2%). However, as shown in previous studies, aggregated results hide regional differences. Developing countries experience a decrease in cereal production of 5–6% based on the CSIRO climate projections, while developed countries such as the U.S. increase their production by 6–9%. The cereal prices present major increases under the HadCM3 (2–20%) and the CSIRO scenarios (4–10%) while the remaining GCMs present even fewer climate change impacts. Their conclusions are consistent with previous studies, especially regarding the heterogeneity of climate change impacts at the regional, but not global level.

Despite the differences among the reviewed studies (especially in the magnitude of their results), a consensus is observed in several issues. First, developing regions may be more negatively affected by climate change than other regions, mainly due to their warmer baseline climates, the major presence of C4 crops that present little CO2 fertilisation, the predominance of agriculture in their economies, and the scarcity of capital for adaptation measures. Second, these studies agree that including the effects of trade in their assessments tends to offset the overall projected impacts of climate change. Third, production in the developed countries benefits from climate change and compensates for the decline projected for developing regions. These three common findings explain the small globally aggregated impacts of food production observed in previous studies. Despite this relatively broad consensus amongst researchers, new questions have arisen regarding the uncertainties of these global impact assessments and the limitations of the economic modelling tools that are currently used. For instance, crop yield projections were mainly based on a limited number of crop models (DSSAT and AEZ), and the same economic model (BLS) was used for economic assessments so that the uncertainties associated with the structure of it could not be explored.

Since the mid-2000s and the release of the IPCCs Fourth Assessment Report (AR4), several improvements in all components of the structural approaches that link biophysical and economic models were observed. Amongst them, many simulations were available from a broader range of more sophisticated climate models (Parry, 2007).In addition, better downscaling techniques for improving the climate input into biophysical models, the emergence of updated versions of crop models, and a combination of biophysical-socioeconomic modelling at a high level of detail and large extent were observed. Furthermore, the use of trade models has expanded, a greater diversity of yield projections is available for consideration, and a major disaggregation of prices by commodity has occurred. Moreover, the first attempts to identify the underlying uncertainty of these approaches appeared at this time. This issue was addressed using a range of plausible biophysical outcomes (Hertel et al., 2010), or by using a wider range of plausible climate scenarios (Nelson et al., 2009, 2010).

To address the coarse aggregates at sectorial and regional levels in the earlier economic assessments and to face the underlying uncertainties of these approaches; Hertel et al. (2010), based their results on the synthesis of values from impact assessments for the Global Trade Analysis Project (GTAP) model. These authors bracket a range of plausible outcomes, estimate the central and tails of the potential yield impacts in 2030, and then use them as exogenous supply shocks in the GTAP model to assess the economic impacts on agriculture. In addition, these authors showed that their central case has only modest price changes, which is consistent with previous global projections (Easterling et al., 2007). However, when the tails of the distribution were used, much greater changes in food prices occurred than reported in other studies, with major average world food price increases in the low productivity scenario (32% for cereals and 63% for coarse grains). These authors emphasise the importance of looking beyond central case climate shocks as well as the importance of considering the full range of possibilities when designing policy responses.

Using a new version of GTAP, Calzadilla et al. (2013) assessed the potential impacts of climate change and CO_2 fertilisation on global agriculture and food prices. This assessment was based on external predictions (Falloon and Betts, 2010; Stott et al., 2006) of changes in precipitation, temperature and river flow for the SRES A1B and A2 scenarios. These authors assessed the impacts of climate change on agriculture according to 6 scenarios (see annex table 1) and applied each scenario to two time periods (2020, 2050). Crop responses were based on Rosenzweig and Parry (1994) for responses to changes in precipitation and temperature; Tubiello et al. (2007) for CO_2 fertilization effects on crop yields; and 3) Darwin et al. (1995) for the runoff elasticities of water supply. As shown in previous studies, the production estimates by these authors decreased and the price increased under both emission scenarios and time periods for most of the crops assessed (all-factors scenario). Higher prices were estimated to occur by 2050 for cereal grains, sugar cane, sugar beet and wheat, with increases of between 39 and 43%.

Nelson et al. (2009, 2010) provides two widely cited studies. Nelson et al. (2010) follows the same method described in the food policy report of 2009 and uses a wider range of plausible economic, demographic and climatic scenarios. At the time, this study was one of the first assessments to combine biophysical and economic models using such a high level of detail and large extent. These authors used the latest updated version of the DSSAT suite of crop models by combining very detailed process based climate change productivity effects into a detail PE model of world agriculture (IMPACT model). In addition, this study utilises three combinations of income and population growth from 2010 to 2050. For each combination, they examine a series of 4 climate scenarios[3] where the

[3] The CSIRO A1B and B1 and the MIROC A1B and B1

baseline is perfect mitigation[4]. Overall, fifteen perspectives on the future are listed that encompass a wide range of plausible outcomes. The main results showed that prices would rise to 31.2% for the rice in an optimistic scenario and to 106.3% for maize in the pessimistic scenario when averaging the four climate change scenarios. Additionally, the prices still increased even with using perfect mitigation scenarios, but to a lesser extent (18.4% for rice in the optimistic scenario to 34.1% for maize in the pessimistic scenario).

Table 4 compares the effects of climate change on the food prices obtained by different studies after the AR4 of the IPCC. As a common finding, most of the studies estimate an increase of prices for 2050 compared with the baseline. On the other hand, when focusing on the magnitude of results, the price effects of climate change are much smaller (or less pessimistic) in general equilibrium simulations than in partial equilibrium simulations. This finding is consistent with other studies, which have been explained by the use of more flexible economic functional forms by CGE models (Ciscar et al., 2009; Nelson et al., 2014; von Lampe et al., 2014).

3.2 Regional economic impact assessments of climate change on EU agriculture

As one of the largest cereal producers and traders, Europe is an important region to assess in terms of the economic effects of climate change on agriculture and how these effects will affect global agricultural markets. In recent years, many studies have assessed the impacts of climate change on EU agriculture. An important portion of these assessments have focused on the biophysical consequences of climate change and evaluating these consequences through literature surveys (Olesen and Bindi, 2002; Lavalle et al., 2009; Olesen et al., 2011), yield response functions focusing on selected regions of Europe (Quiroga and Iglesias, 2009), or linking biophysical and statistical models for different agro-climatic regions (Iglesias et al., 2009). Other studies have assessed the economic impacts of climate change on EU agriculture by basing their methodologies on spatial-analogue approaches (Reidsma et al., 2007, 2009). Furthermore, economic indicators for Europe that integrate biophysical and economic models have primarily resulted

[4] Baseline defined by Nelson et al. (2010). Here the results assume that all GHG emissions ceased in 2000 and that the climate momentum in the system stopped.

Table 4: Price changes comparison between different studies after AR4

Source	Price (% changes)
Nelson et al. (2010)	Range among scenarios[a] Maize (87.3 – 106.3) Rice (31.2 – 78.1) Wheat (43.5 – 58)
Hertel et al. (2010)	Low productivity scenario: Cereals (32) Coarse grains (64)
Calzadilla et al. (2013)	All-factors scenario Wheat ($\sim$ 40) Cereal grains ($\sim$ 45) Rice ($\sim$ 20) Oilseed ($\sim$ 30)

[a] Mean across climate scenarios CSIRO and MIROC - SRES A1B and B1;$\sim$ approx. equal

from global-scale analysis (Parry et al., 2004; Nelson et al., 2010) and have delivered aggregated results. Evidence from peer-reviewed literature of the structural economic assessments at the EU regional level was sparse before the mid-2000s and became more frequent during and after 2009.

Under the PESETA[5] project, Ciscar et al. (2009) assessed the potential economic effects of climate change on the EU agricultural sector.These authors obtained climate data that were based on two SRES emission scenarios that were used as input in two combinations of GCMs and Regional Climate models (RCMs) for 2020 and 2080. The DSSAT crop growth models were used to calculate the biophysical impacts and derive crop production functions for the nine agro-climatic regions of Europe. These yield functions were used with a spatial agro-climatic database to conduct a Europe-wide spatial analysis of crop production vulnerability to climate change. Finally, productivity shocks were introduced in GTAP as land-productivity-augmenting technical changes over the crop sector in each

[5] Projection of Economic impacts of climate change in Sectors of the European Union base on boTtom-up.

region, resulting in changes in the GDP. Their results showed significant regional differences between northern and southern European countries, with Mediterranean countries being the most affected.

The PESETA project not only assesses the potential effects of climate change on agriculture but also covers other market impact categories, such as river floods, coastal systems and tourism. In one of the latter stages of this project, the impacts of these four sectors were integrated into CGE model GEM-E3 to obtain a comparable vision of the effects across the sector. Ciscar et al. (2011) presents a detailed description of this last stage of the project and assesses the potential impacts of climate change in Europe in the four market impact categories. The results related to the agricultural sector show important regional disparities. The southern regions present high yield losses under warming scenarios. Central Europe presents moderate yield changes in all scenarios. The northern region presents positive effects of climate change in all scenarios and is the only region with net economic benefits, mainly due to agriculture.

Both of the above works mentioned mark and important step in the regional assessment of the impacts of economic climate change on agriculture in the EU. These studies are the first regionally focused, quantitative, integrated assessments of the effects of climate change on the vulnerable aspects of the European economy and its overall welfare. These studies resulted from the need for further detail and use a methodology that integrates a set of high-resolution climate change projections, detailed impact modelling tools and a regional focus integrated into an economic framework. Both works paved the way for additional studies of European regional assessments regarding the economic impacts of climate change on agriculture.

Shrestha et al. (2013) took the next step to improve economic regional impact assessments of EU agriculture. These authors analysed the economic impacts of climate change by linking climate data and biophysical and economic models at a high disaggregated regional level. The BIOMA (Biophysical models application) platform generates yield change data, which is used in the partial equilibrium CAPRI model to predict economic impacts. As a further advancement, Shrestha et al. (2013) simulated results for the EU at the sub-member (NUTS-2[6]) level

[6] Nomenclature of Territorial Units for Statistics with 272 NUTS 2 regions in EU27

while modelling global world agricultural trade. These authors used two climate scenarios (warm and mild) that were both based on the A1B emission scenario and used as inputs for two combinations of GCMs and Regional Climate models (RCMs) for 2020. These authors showed minor effects at the EU level and stronger effects at the regional level, which were consistent with the results shown in previous studies.Shrestha et al. (2013) showed that the estimated regional effects varied by a factor of up to 10 relative to the aggregate EU impacts. Furthermore, the simulation results show how the price adjustments decreased the response of the agricultural sector to climate change. This study marked another landmark in European regional assessments because it showed regional disaggregated results for the EU. These results allowed us to better understand the regional disparities that climate change can cause in agriculture depending on the location or sector. However, the results of this research were subject to several limitations, including the assumption that crop yields will remain unchanged in the non-EU countries.

Blanco et al. (2014a) filled this gap and introduced several improvements in the European regional impact assessment. These authors used the same methodological approach as Shrestha et al. (2013) but considered climate-induced changes in crop yields for non-EU countries. In addition, these authors used the WOFOST (World Food Studies) crop model (through the BIOMA platform) to simulate the effects of climate change on yield at high grid resolutions across the EU and up to 2030. Simulations were performed with and without the effects of CO2 fertilisation. In addition, they increase the crops covered compared with previous studies. Simulations for non-EU regions were based on a study performed for the 2010 World Development Report (Müller et al., 2010). The main results of this study are consistent with those of previous works (Ciscar et al., 2009; Shrestha et al., 2013), that showed that the impacts of climate change on crop yields vary widely across EU regions and crops, while the aggregate results hide these significant disparities. According to global impact assessments (e.g., Parry et al., 2004) their simulations were strongly influenced by carbon fertilisation, which shows greater production under a full carbon fertilisation scenario. Regarding the main conclusion, the authors highlight the need for using price endogenous models to assess the impacts of climate change on production, mainly due to the counterbalanced effects of crop prices on final yield effects.

Table 5: Comparison of the economic results between EU-regional assessments

Source	Climate scenario (GCM-forcing)	Production changes in EU (% change)	Price changes in EU (% change)	Agr. income changes in EU (% change)
Shrestha et al. (2013)[a]	Mid-Global HIRHAM5-ECHAM5 (A1B)	Cereals (+2.8) Oilseeds (-4.8)	Cereals (–2.4) Oilseeds (+2.9)	–0.02
	Warm-Global HadRM3Q0 HadCM3 (A1B)	Cereals (+9.6) Oilseeds (–1.2)	Cereals (–10.2) Oilseeds (–6.7)	–0.02
Blanco et al. (2014a)[b]	ECHAM-CO_2 HIRHAM5-ECHAM5 (A1B)	Range across crops Cereals ($\sim$ 1 to –8) Oilseeds ($\sim$ 0 to –12)	$\downarrow$	–4.5
	Hadley-CO_2 HadRM3-HadCM3 (A1B)	Cereals ($\sim$ 0 to –14) Oilseeds ($\sim$ 1 to –12)	$\downarrow$	–0.2

[a] Time horizon 2020; [b] Time horizon 2030; $\downarrow$ world price effects drive down EU crop prices; $\sim$ approximately equal to

Table 5 shows economic indicators presented by two of the studies mentioned above. Although these studies employed similar methodologies, their results are very difficult to compare, mainly due to the differences in the time horizons of the studies. However, one interesting result is the observed differences between the climate scenarios and the changes in agricultural income. Although both studies used the same economic model to estimate the socio-economic responses (in contrast with Shrestha et al., 2013), Blanco et al. (2014a) presented more negative results and higher differences between the climate scenarios. One possible explanation for this result is the effect of the climate change simulation in non-EU countries that was considered by Blanco et al. (2014a).

4 Economic impact assessments under new scenarios

Since AR4 (Parry, 2007), new global socio-economic and environmental scenarios for climate change research have emerged. These scenarios are richer, more diverse and offer a higher level of regional detail compared with previous SRES scenarios (Field et al., 2014). The AR5 of the IPCC distinguishes between two types of scenarios. The Representative Concentration Pathways (RCPs), which were named according to their radiative forcing level in 2100, and the Shared Socioeconomic Pathways (SSPs), which represent assumptions regarding the state of the global and regional society as it evolved over the course of the 21st century. The RCPs include one scenario that results in a very low forcing level (RCP2.6), two stabilisation scenarios (RCP4.5 and RCP6), and a high scenario (RCP8.5), which corresponds to a high greenhouse gas emission pathway (van Vuuren et al., 2011). By contrast, the SSPs include five different pathways, each of which is assembled along the axes of the challenges to mitigation and adaptation to climate change. These SSPs contain population and gross domestic product (GDP) developments and semi-quantitative elements (Kriegler et al., 2012).

Over the last two years, most of the impact assessments that based their results on the new scenarios have focused on quantifying the uncertainty that underlies their approaches. Amongst the methodologies used to provide insights into modelling uncertainties, the comparison of results among different modelling approaches has had an important development. Several exercises within the framework of the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP) have been performed. Focusing on agricultural oriented studies Rosenzweig et al. (2013) used all four RCPs scenarios with 5 global climate models and 7 Global Gridded crop models (GGCMs) to quantify the global effects of climate change on major crops. This research is an important development and provides insights into crop modelling uncertainties.

If we turn our attention to economically oriented studies based on structural modelling approaches, only a few studies quantified the economic impacts of climate change that were derived from the RCPs and SSPs scenarios. At a global level, Nelson et al. (2014, 2013), presented results from a global economic model inter-comparison exercise with harmonised data for future yield changes. The main aim of these exercises was to provide uncertainty estimates for the economic phase of the impact assessment process. Nelson et al. (2013) analysed the endogenous responses of nine global economic models to standardised climate change scenarios produced by two GCM and five crop models under the RCP8.5 and the SSP2[7] These authors showed a global mean yield decrease of 17% by 2050 without CO_2 fertilisation. This mean was between four crop groups and 13 regions of the globe, with a standard deviation of $\pm$ 13% resulting from the differences in the impacts across the crops and regions and the diversity of the GCM and crop models. The analysis of the endogenous economic responses showed that the yield loss was reduced to 11% and that the area of major crops increased by 11%. Both effects resulted in a mean production decrease of 2% and a final price increase of 20%. As a main finding, these results indicated that all economic models[8] transferred the shock effects to the response of economic variables. These authors highlighted that the analyses only focused on the biophysical effects of climate change, underestimate our capacity to respond.

Using a similar approach, Nelson et al. (2014) supplied yield projections from two global crop growth models for two implementations of the RCP8.5 emission scenario in two GCMs, all under the SSP2. These scenarios were designed to assess the upper end of climate change impacts (omitting CO_2 fertilisation and adaptation mechanisms). Ten global agricultural models (see Annex Table 2) used these productivity shocks as inputs to generate different economic responses. They analysed the effects of individual endogenous responses, such as prices, yield and area changes. Then, they broke down the effects of climate change shock to identify the importance of the adjustment of three components in the model response (consumption, area and yield). By focusing on the individual responses, the authors presented results for five commodities/commodity groups, which were collectively called CR5 (coarse grains, rice, oilseeds, sugar and wheat). The results showed a price increase relative to the reference scenario across all the models with high variations between the economic models and crop models and small variations across the climate models. All models showed higher prices in 2050,

[7] Population of 9.3 billion by 2050 and global GDP triples.
[8] The economic models used by Nelson et al. (2013) are detailed in the annex.

which ranged between 3.0 to 78.9% for the CR5 aggregates and between 2.1 to 118.1% for the coarse grains (see Table 6).

Using the same scenarios used by Nelson et al. (2014), Witzke et al. (2014) simulated long-term economic responses by using the PE model CAPRI. As shown in previous studies, these authors observed moderate impacts on the global agricultural markets at the aggregated level and strong variations across regions. At the global level, these authors observed agricultural price increases of 6% to 13% relative to the reference scenario. As shown by Nelson et al. (2014), these authors showed stronger price increases in the HadGEM2-ES scenario. In addition, these authors showed major variations in the price changes across regions and across commodity aggregates. For example, wheat, coarse grains and rice increase their prices by 28% to 56% by 2050, and sugar prices did not increase by more than 4% in the four climate scenarios.

Table 6 compares some of the economic results presented by the three studies mentioned above for a selected commodity group. Focusing on price changes, we divided the results presented by Nelson et al. (2014) into those released by PE and CGE models. The greatest variation occurred between the PE models rather than amongst the CGE models, with a higher median final price increase for coarse grains. Consistent with previous studies, the magnitude of the price changes was smaller in the CGE models than in the PE models.

At the European level, a recent scientific report by Blanco et al. (2014b) assessed the impacts of climate change at a regionalised level within the EU under the new RCPs and SSPs scenarios. These authors used a similar approach to that used by Blanco et al. (2014a). However, they developed important advances compared with previous works. Specifically, their simulations were based on the new RCPs and SSPs scenarios; the changes in crop yields for non-EU regions were based on a highly detailed database; there were more crops covered by the biophysical simulations; and there was a wider range of plausible climate scenarios. These authors considered six simulation scenarios that focused on the RCP8.5 and the "middle of the road" socio-economic scenario (SSP2). Moreover, these authors used three GCMs and considered the effects with and without CO_2 fertilisation. Generally, their results were not different from those of previous studies, and they showed that moderate global changes in production were mainly driven by interregional adjustments in production, consumption and trade (both

Table 6: Range of price percent change between climate scenarios by 2050 for coarse grains

Source	Price (range of % changes)	Endogenous yields (range of % changes)
Nelson et al. (2009)	Average producer price 20	Average yield mean 11 (mean in production: -2)
Nelson et al. (2014)	GCE models range 2.1 to 43.2 (mean: 12.25) PE models range 2.5 to 118.1 (mean: 37.9)	GCE models range –28.8 to –1.9 (mean: –12.3) PE models range –26.4 to –1.5 (mean: –12.8)
Witzke et al. (2014)	28 to 49	–12 to –5[a]

[a] Impact on global production by commodity aggregate (CGR).

with and without the effects of CO_2). Additionally, the direction of the effects is clearly influenced by the magnitude of carbon fertilisation. Similar production patterns and price change variations were observed and compared with global impact assessments. The variation increases as the geographical resolution of the results increases. For example, wheat production at the global level increased by 0.9 to 2.3% in the climate scenarios considering CO_2 fertilisation. Regarding EU production, the effects varied from –0.9 to 2.2%. Important variations were also observed across different commodities. Within the EU and in the same scenario (HadGEM2-CO_2), the results showed a decrease in production of 0.1% for rapeseed and a decrease of 12.4% for maize.

Corresponding with current global comparison exercises, Frank et al. (2014) presented a recent analysis of the impacts of climate change on the agricultural sector from a European perspective by using two European focused global PE models. These authors quantified the economic impacts of climate change up to 2050 and applied and linked the partial equilibrium models CAPRI and GLOBIOM-EU. For comparison, these authors compare their results under the same set of scenarios based on the RCP8.5 and SSP2 scenarios. In addition, these authors considered a baseline scenario and two climate change scenarios (S3 and S6) picked from the full set of AgMIP scenarios (von Lampe et al., 2014). Overall, Frank et al. (2014) presented findings that were similar to those of the global assessments regarding the endogenous responses buffer to exogenous yield shocks due to climate change. At the global level, the exogenous yield shock varied from –11% (S3) to –21% (S6) when compared with global demand and production, which decreased by 4–6% in S3 and 7–10% in S6. At the European level, exogenous shocks of –11% (S3) and –16% (S6) were translated into production decreases of 3–4% in S3 and 4–7% in S6. When comparing the economic results and global studies, price was the most sensitive parameter that was affected by climate change. Although CAPRI predicted stronger price effects and smaller demand effects, their differences in a context of a larger model comparison exercise become negligible.

5 Common findings and future research directions

Economic impact assessments of climate change in agriculture have become an important tool for understanding the physical and socio-economic responses of the agricultural sector to future climate change scenarios. Amongst the different approaches and methodologies used, structural approaches that integrate biophysical and economic models have presented an important evolution between the 1990s and today. To analyse this evolution from the range of studies reviewed here, we identified six different methodologies based on their geographical coverage and treatment of the economy. We identified three methods with global coverage that use the PE, CGE or BLS models and three modelling approaches at the regional level that use the PE, CGE or farm models.

Based on this categorisation, we focused on five of the six identified methodologies. Considering those studies in which the economic model captures the market feedback. Thus, we considered the studies that used projected yield impacts as inputs for general or partial equilibrium models of commodity trade. From this framework, we synthesised and analysed the evolution of these methodologies at global and EU levels between the 1990s and today.

In this review, we observed the evolution of the entire impact modelling chain, from early assessments onward, at the global and EU levels. Better resolution, better data availability, and the use of more biophysical and economic models are just a few of the major advances that we have mentioned in this literature survey. In addition, we have highlighted some of the major milestones within this specific approach and the methods reviewed here. These methods spanned from the first assessments considering CO2 fertilisation and adaptation measures to those presenting updated emissions scenarios that allowed for more accurate climate change projections and an increasing number of studies with better spatial resolution. Beyond their assessment of the effects on agricultural production and prices, these studies encompassed important issues regarding the impacts of climate change, such as food security, the distributional effects of climate change, and the evaluation of several adaptation measures. Finally, we review the last studies at the global and EU levels based on the new RCPs and SSPs scenarios. We present their main features and show how differences in the key outputs from past modelling exercises have resulted in new assessments looking for provide more insights into modelling uncertainties. Despite these differences, we have extracted common findings for several issues.

5.1 Common findings

This review was based on studies with very different designs and assumptions that shared a common methodology within the framework of the structural approach. Despite their differences, we identified the following important common findings.

Aggregated results at global and regional levels hide the effects at more disaggregated scales. This is particularly evident for production changes and other endogenous responses, such as land use or income. From the global studies reviewed here, most of them present moderate globally aggregated impacts on world food production with important negative impacts in developing regions (e.g., Parry et al., 1999). The same pattern was observed in the EU studies, where most of them presented small effects at the EU aggregate level and greater effects at the regional level (Shrestha et al., 2013).

All of the studies, independent of their geographical coverage or economic treatment, confirm the important role of trade and inter-regional adjustments as buffers of projected climate change impacts. Most of the economic models used in the studies reviewed here have transferred a portion of the climate change shock to trade responses and international price changes, resulting in lower and more reliable results than the assessments based only on domestic yield effects (Tobey et al., 1992).

In addition, economic models transfer the climate change shock to the production side of the economic model, which helps offset the primarily exogenous yield impact by resulting in a final lower endogenous yield response. Along with the issue mentioned above, this economic adjustment implies that the analyses that only focus on the biophysical effects of climate change significantly underestimate our capacity to respond (Nelson et al., 2013).

Of the global assessments reviewed, it was commonly agreed that the impacts of climate change will be more negative in developing countries than in developed countries. Several authors have attributed this to biophysical and economic reasons. From the biophysical side, more negative impacts are expected because of 1) the warmer baseline climate of developing countries and the effects of climate change on them due to increasing temperatures and 2) the important share of developing countries that tend to rely more on C4 crops with less significant responses to increasing levels of CO_2 (Lobell and Burke, 2010a). From an economic point of view, increasing world food prices due to climate change may result in 1) the reduction of real income in developing countries, where food expenditure shares are higher, and 2) important impacts on food access where consumption is more price elastic.

Finally, regional disparities were observed in EU regional studies. Most of the studies reviewed agree regarding the significant regional differences within Europe. Decide what regions are winners or losers regarding climate change depend on several factors (e.g., climate scenario, crop model used, adaptation measures, and geographical features). However, most of the studies reviewed here indicated more negative impacts in southern countries than in northern countries.

5.2 Future research directions

In this section, we have summarised the evolution of the structural approach and its methods based on the integration of biophysical and economic models. In addition, we have summarised its evolution through the last two decades, compared their main economic outputs, and extracted common findings. However, several unresolved challenges remain that are often related to modelling shortcomings. These shortcomings must be used as clues regarding the direction of future research. Below, we provide several areas for future research based on this specific approach and the methodologies reviewed here.

Lack of detail

The global and EU assessments reviewed here have mainly focused on the impacts of climate change on a few crops (mainly wheat, maize, soybean and rice). The number of crops covered by these approaches has increased since the mid-2000s; however, most of these studies ignore the impacts of important commodities. For example, the responsiveness of grasslands and animal productivity to climate change are rarely considered. Several commodities within the economic impact assessment could generate more plausible results (considering the cross-sectoral relations in agricultural markets). By contrast, aspects such as those related to the responses of other crop yield drivers, such as weeds, pests and diseases have been excluded from these economic assessments. Furthermore, few studies have considered different adaptation options within this type of assessment. Most of these studies have assessed minor agronomic management changes (e.g., sowing dates), leaving several other options that could have important effects over the final results (e.g., the tolerance of the crop variety to heat or water logging from heavy rainfall). Finally, a lack of modelling approaches are available that consider the impacts of climate change on agriculture with closely related sectors. For example, the impacts of global warming on water and energy economic sectors will directly affect the final endogenous responses of economic models, which will probably understate the final negative effects.

Validation of economic models

Several authors have mentioned that model validation is one of the main challenges for future research regarding modelling the effects of climate change on agriculture (e.g., Schmitz et al., 2014). Among the issues discussed in the literature, several difficulties imply model validation in the context of long-term projections (Schwanitz, 2013); the methods used for model validation and their limitation; and the lack of guidelines and standards for testing these models (Bonsch et al., 2013).

When focusing on the studies reviewed here, we observed several issues related to the problems mentioned above. First, information was lacking regarding the validation of the economic model used in these studies. Only three of the reviewed studies explicitly mentioned that their economic components were subjected to a validation process. Amongst these studies, all of them based the validity of their economic models in previous studies to validate their internal structure (Kane et al., 1992) or their output behaviour (Fischer et al., 2005; Hertel et al., 2010). In this context, several authors indicated that the validation process should aim to confirm that the models generate the "right output behaviour for the right reasons" (Barlas, 1996). Thus, the validation tests must assure both "structural validity" and "behavioural validity". However, no validation process was mentioned in these studies that encompasses both objectives. Furthermore, within the validation of the output behaviour underlies the problem of the future behaviour of empirical data. Thus, comparisons with observed data are only possible in retrospect (through backcasting or hindcasting methods). Although this is considered a reliable approach, there is a risk of over calibrating models to past processes that might not necessarily be the processes driving future developments (Uthes et al., 2010).

Second, after the new scenarios, we observed a concentration of validation processes by comparing different model outputs. Although this process has been used to provide insights regarding modelling uncertainties, it has also been used to support claims of a model's validity. The model intercomparison exercises mentioned in this review (Nelson et al., 2014; Frank et al., 2014) are examples for model output comparisons. Although, it is important to test a model's validity, caution must be used if calibration is involved in the process (Bonsch et al., 2013).

Data and input parameters

More work is needed regarding estimations of the key parameters in economic models. The values of these estimations must be determined consistently with the availability and quality of data. However, the absence of data availability and quality is one of the major constraints faced by the modelling community. Among the studies reviewed here, several authors have highlighted this problem and pointed out challenges that they must overcome due to extremely poor data sources in critical areas, such as data for supply and demand parameters (Nelson et al., 2010). Additionally, a low diversity of available data and significant proportions of data are synthetically constructed rather than based on direct empirical observations. Nelson et al. (2014) confirmed that these problems are major challenges and have underlined that many of the parameters used in the economic models *"have limited econometric and validation studies to back them up with significant confidence"*. Future research must aim to strengthen elementary economic estimations, and data should be shared within the community.

Model structure and market failures

The structure of the economic models reviewed here all follow the same basic neoclassical theory. Thus, these models use several simplifying assumptions, including the rationality of consumers and producers and the absence of market imperfections. Consequently, several findings, such as the role of trade as a buffer of climate impacts, must be treated with caution. For instance, welfare estimates through simulation models are characterised as an aggregate of consumer and producer rent. These aggregate estimates mask significant differences in impacts across regions and the population (Arent et al., 2014). On the other hand, with the absence of market imperfections, externalities are not considered when, for instance, trade barriers are abolished. This may result in an incorrect vision of reality. Future research must aim to assess the real possibilities that exist to incorporate market imperfections in these types of methodologies.

Food security

Food security is probably one of the most important issues regarding the impacts of climate change on agriculture. Nevertheless, food security has been characterised by its complexity and multiple dimensions, including food availability, food access, food utilisation, and stability. These features and the interaction between these dimensions have resulted in enormous challenges for researchers and modelling teams that aim to evaluate the impacts of climate change on food security. The structural approach, and the methods reviewed here have contributed to understanding some of the effects of climate change. However, several challenges remain.

First, the studies reviewed here have been unevenly distributed over two of the four dimensions that food security encompasses (Schmidhuber and Tubiello, 2007; Wheeler and von Braun, 2013). Until the mid-2000s the global assessments reviewed here were able to focus mainly on the impacts on food availability. By contrast, in the late 2000s, Nelson et al. (2010) assessed the impacts of climate change on agricultural markets and connected the economic consequences of food availability drivers to food access and food utilisation. Second, these studies rely on a few economic models to assess the effects of climate change on food security, including the BLS model within the modelling framework of the IIASA system and through the PE model IMPACT. Thus, it is important to add to this type of assessment new economic models to explore the uncertainties associated with modelling the impacts of climate change on food security. Some efforts in this direction have been reported under the FACCSU-MACSUR project, with the PE model CAPRI[9]. Finally, food prices at the producer level provide little information about the burden for consumers. Future modelling efforts should consider more indicators at the consumer levels, such as consumer prices, food expenditure shares, the nutrition values of food baskets, food access or food utilisation.

Adaptation policies

Finally, another important issue encompassed by the structural approach and their methods is the assessment of climate change adaptations. One particular dimension of the adaptation question is related to adaptation policies. Several studies have assessed the effects of trade liberalisation as a tool for adapting to climate change (e.g., Randhir and Hertel, 2000). However, it is still necessary to assess a wider range of adaptation policies in modelling frameworks (Easterling et al., 2007). An interesting aim of future research could be to determine the effects of adaptation policies that increase public spending on research and technology. On-going efforts in this direction have been reported in Ignaciuk and Mason-D'Croz (2014). By contrast, several potential adaptation options extend beyond in food production

[9] See http://macsur.eu/index.php/products

adaptations. For instance, storage policies have not been analysed although they largely influence food prices.

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Appendix

Table 1: Global and EU regional economic assessments previous to RCPs and SSPs scenarios

Reference	GCMs Emission scenarios Climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional Scope	CO_2 fertilization	Time Horizon	Farm-level Adaptation measures
Global economic impact assessments							
IPCC FAR (1990)							
Tobey et al. (1992)		Crop responses to climate change obtained from external studies	SWOPSIM (PE)	Global (13 regions)	No		No
Kane et al. (1992)		Crop responses to climate change obtained from external studies	SWOPSIM (PE)	Global (13 regions)	No		No
Rosenzweig and Parry (1994)	3 Low resolution GCMs (GISS; GFDL; UKMO)	Crop models and a decision support system developed by IBSNAT* (1989) (DSSAT v2.1)	BLS	Global (34 regions)	Yes	2060	Yes
IPCC SAR (1995)							
Special Report on Regional Impacts of Climate Change (IPCC, 1997)							
Parry et al. (1999)	5 Higher resolution GCMs 1 emission scenario 2 climate change scenarios • HadCM2-IS92a (four ensemble members) • HadCM3-IS92a	DSSAT (v2.1)	BLS	Global (34 regions)	Yes	2020 2050 2080	Yes

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Table 1 – *Continued from previous page*

Reference	GCMs Emission scenarios Climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional Scope	CO_2 fertilization	Time Horizon	Farm-level Adaptation measures
Fischer et al. (2002)	4 GCMs 5 SRES emission scenarios 12 climate change scenarios • HadCM3-(A2;B2;B1;A1FI) • CSIRO-(A2;B2;B1;A1B) • CGCM2-(A2;B2) • NCAR-(A2;B2)	Agro-ecological zones (AEZ) model	BLS	Global (34 regions)	Yes	2080	Yes
Parry et al. (2004)	1 GCM 4 SRES emission scenarios 7 climate change scenarios • HadCM3-A1FI • HadCM3-A2 with 3 ensemble members (a,b,c) • HadCM3-B1a • HadCM3-B2 with 2 ensemble members (a,b)	DSSAT (v 2.1)	BLS	Global (34 regions)	Yes	2020; 2050; 2080	Yes
Fischer et al. (2005)	5 GCMs; 5 SRES emission scenarios; 14 climate change scenarios: • HadCM3-(A2;B2;B1;A1FI) • ECHAM (A2;B2) • CSIRO-(A2;B2;B1;A1B) • CGCM2-(A2;B2) • NCAR-(A2;B2)	FAO/IIASA Agro-ecological zone model (AEZ)	BLS	Global	Yes	2080	Yes

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Table 1 – *Continued from previous page*

Reference	GCMs Emission scenarios Climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional Scope	CO_2 fertilization	Time Horizon	Farm-level Adaptation measures
		IPCC AR4 (2007)					
Nelson et al. (2009)	2 GCMs; 1 SRES emission scenario; 2 climate change scenarios (with and without CO_2 fertilization): • NCAR-A2 • CSIRO-A2	DSSAT (v4.0)	IMPACT (PE)	Global (281 FPUs)	Yes	2050	Yes
Nelson et al. (2010)	2 GCM; 2 SRES emission scenarios; 4 climate change scenarios • CSIRO-(A1B;B1) • MIROC-(A1B;B1)	DSSAT (v4.5)	IMPACT (PE)	Global (281 FPUs)	No	2050	Yes
Hertel et al. (2010)		Synthesis of values from the literature for the GTAP regions and six commodities	GTAP (CGE)	Global (34 regions)	Yes	2030	No
Calzadilla et al. (2013)	From Falloon and Betts (2006) and Stott et al. (2006). 1 GCM (HadGEM1-TRIP); 2 SRES emission scenarios (A1B;A2). Six scenarios: • Precipitation-only • Precipitation-CO_2 • Precipitation-T°-CO_2 • Water-only • Water-land • All-factors	Regional crop yield responses to changes in precipitation and temperature are based on Rosenzweig and Iglesias (1994) CO_2 fertilization effect on crop yields are based on information presented by Tubiello et al. (2007) Runoff elasticities of water supply estimated by Darwin et al. (1995)	GTAP-W (CGE)	Global (34 regions)	Yes	2020 2050	No

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Table 1 – *Continued from previous page*

Reference	GCMs Emission scenarios Climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional Scope	CO_2 fertilization	Time Horizon	Farm-level Adaptation measures
European regional economic impact assessments							
Ciscar et al. (2009)	2 GCMs; 3 RCMs; 2 SRES (A2 and B2); 5 climate change scenarios: 1 scenario for 2020: • RCA-ECHAM (A2) 4 scenarios for 2080: • HIRHAM-HadAM3h (A2;B2) • RCAO-ECHAM4 (A2;B2)	DSSAT-for Europe World yield changes based on Parry et al 2004	GTAP and GEM-E3 (CGE)	Europe (5 regions)	Yes	2020 2080	Yes
Ciscar et al. (2011)	2 GCMs; 2 RCMs; 2 SRES emission scenarios; 4 climate change scenarios • HIRHAM-HadAM3h (A2;B2) • RCAO-ECHAM4 (A2;B2)	DSSAT	GEM-E3 (CGE)	Europe (5 regions)	Yes	2080 (2010)**	Yes
Shrestha et al. (2013)	2 GCMs; 2 RCMs; 1 SRES emission scenarios; 2 climate change scenarios • HadRM3Q0-HadCM3 (A1B) • HIRHAM5-ECHAM5 (A1B)	BIOMA platform	CAPRI (PE)	Europe (280 NUTS 2 regions); Global (77 countries in 40 trade blocks)	Yes	2020	Yes

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Table 1 – *Continued from previous page*

Reference	GCMs Emission scenarios Climate projections	Biophysical model (estimation of potential changes in crop yields)	Economic model	Regional Scope	CO_2 fertilization	Time Horizon	Farm-level Adaptation measures
Blanco et al. (2014a)	2 GCMs; 2 RCMs; 1 SRES emission scenarios; 2 climate change scenarios • HadRM3-HadCM3 (A1B) • HIRHAM5-ECHAM5 (A1B)	WOFOST (BIOMA platform)	CAPRI (PE)	Europe (280 NUTS 2 regions); Global (77 countries in 40 trade blocks	Yes	2030	No

**International Benchmark Sites Network for Agrotechnology Transfer; ** Quasi-static analysis / economic effects of future climate change (projected for the 2080s) on the 2010s economy.*

Table 2: Global and EU regional economic assessments post RCPs and SSPs scenarios

Reference	GCMs/RCMs Emission scenarios Climate projections	Biophysical model	Economic model	Regional Scope	CO_2 fertilization	Time Horizon
Global economic impact assessments						
Nelson et al. (2013)	2 GCMs 1 RCPs 2 climate change scenarios: • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5)	5 Crop growth models: • DSSAT • EPIC • LPJmL • pDSSAT • PEGASUS	5 CGE models: • AIM • ENVISAGE • FARM • GTEM • MAGNET 4 PE models • GCAM • GLOBIOM • IMPACT • MAgPIE	Global	No	2050
IPCC AR5						
Nelson et al. (2014)	2 GCMs 1 RCPs 2 climate change scenarios: • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5)	2 Crop growth models: • DSSAT • LPJmL	5 CGE models: • AIM • ENVISAGE • FARM • GTEM • MAGNET 4 PE models • GCAM • GLOBIOM • IMPACT • MAgPIE	Global	No	2050

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Table 2 – *Continued from previous page*

Reference	GCMs/RCMs Emission scenarios Climate projections	Biophysical model	Economic model	Regional Scope	CO_2 fertilization	Time Horizon
von Lampe et al. (2014)	2 GCMs 1 RCPs 2 climate change scenarios: • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5)	2 Crop growth models: • DSSAT • LPJmL	5 CGE models: • AIM • ENVISAGE • FARM • GTEM • MAGNET 4 PE models • GCAM • GLOBIOM • IMPACT • MAgPIE	Global	No	2050
Witzke et al. (2014)	2 GCMs 1 RCPs 2 climate change scenarios: • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5)	2 Crop growth models: • DSSAT • LPJmL	1 PE model • CAPRI	Global	No	2050
			European Regional economic impact assessments			
Blanco et al. (2014b)	3 GCMs 1 RCPs 3 climate change scenarios (with and without CO_2): • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5) • MIROC (RCP8.5)	2 Crop growth models: • LPJmL (global) • WOFOST (EU)	1 PE model • CAPRI	Europe (280 NUTS 2 regions); Global (77 countries in 40 trade blocks)	Yes	2050

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Table 2 – *Continued from previous page*

Reference	GCMs/RCMs Emission scenarios Climate projections	Biophysical model	Economic model	Regional Scope	CO_2 fertilization	Time Horizon
Frank et al. (2014)	2 GCMs 1 RCPs 2 climate change scenarios: • HadGEM2-ES (RCP8.5) • IPSL-CM5A-LR (RCP8.5)	2 Crop growth models: • DSSAT • LPJmL	2 PE models • CAPRI • GLOBIOM-EU	Global-EUROPE	No	2050

Table 3: Main features and differences between economic models used for the assessment of climate change impact on agricultural markets

	PE model	**BLS trade model**	**GE model**
Scope of application	Agricultural Sector	Regional subset of economies	Global Economy
Underlying economic theory	Partial equilibrium (agri-markets)	General equilibrium highly focused on agriculture	General Equilibrium
Exogenous variables	Policy, Behavioural parameters	Policy, Macroeconomic variables, Technical Progress, Shifts in lifestyles.	Policy, Macroeconomic variables
Model Outputs	Production consumption, prices and trade in some markets	Food Production, Food prices, Number of people at risk of hunger	Production, consumption, prices, trade levels and welfare
Representation of differences between economies	Parametric differences between regions	Linked individual country models; Differences in parameters for models with common structure	Parametric differences between regions
Strengths	Provides much product detail than BLS and GE models; Ability to flexibly integrate a wide range of policy instruments; Facilitates both the data-handling aspects as well as the interpretation of results.	Can capture more regional economic and institutional details than GE models (National models account with greater commodity detail).	Provides a complete representation of national economies; Takes in to account the interactions between the agricultural sector and the rest of the economy; Important in a context where linkages from the farm to the non-farm sectors are significant
Weaknesses	Limited capability to handle structural differences between economies; Only suites for policy analysis when the linkages with the rest of the economy are small	Individual country models may make it difficult to disentangle model results into the effects of exogenous events on the one hand and differences in theories on the other hand; Difficulties in terms of consistency and maintenance.	Limited capability to handle structural differences between economies; Often highly aggregated; Rough representation of policies.